THE STATUS OF CROSS SECTION MEASUREMENTS FOR NEUTRON-INDUCED REACTIONS NEEDED FOR COSMIC RAY STUDIES. J. M. Sisterson, Northeast Proton Therapy Center, Massachusetts General Hospital, 30 Fruit Street, Boston, MA 02420. jsisterson@partners.org

Introduction: Cosmic ray interactions with lunar rocks and meteorites produce small amounts of radionuclides and stable isotopes. Advances in Accelerator Mass Spectrometry (AMS) allow production rates to be measured routinely in well-documented lunar rocks and meteorites. These measurements are analyzed using theoretical models to learn about the object itself and the history of the cosmic rays that fell on it [e.g. 1, 2].

Good cross section measurements are essential input to the theoretical calculations. Most primary cosmic ray particles are protons so reliable cross sections for proton-induced reactions are essential. A cross section is deemed accurate if measurements made by different experimenters using different techniques result in consistent values. Most cross sections for proton-induced reactions are now well measured [e.g. 3, 4].

However, good cross section measurements for neutron-induced reactions are still needed. These cross sections are required to fully account for all galactic cosmic ray interactions at depth in an extraterrestrial object. When primary galactic cosmic ray (GCR) particles interact with an object many secondary neutrons are produced, which also initiate spallation reactions. Thus, the total GCR contribution to the overall cosmogenic nuclide archive has to include the contribution from the secondary neutron interactions. Few relevant cross section measurements have been reported for neutron-induced reactions at neutron energies > ~20 MeV [5, 6].

The status of the cross section measurements using quasi-monenergetic neutron energies at iThemba LABS, South Africa and 'white' neutron beams at Los Alamos Neutron Science Center (LANSCE), Los Alamos are reported here.

Measurement Techniques: Two different techniques are used to measure the cross sections of neutron-induced reactions.

In both techniques, monitor foils are included in the target stacks. These monitor foils include C, Al, Ti, Fe, Ni, Cu and Au. Several reactions, particularly those initiated in Al, Ni and Au, have been identified as promising monitor reactions.

The first technique uses quasi-monoenergetic neutron beams generated by 80, 120 or 160 MeV protons on a Be target at iThemba LABS, South Africa. In each irradiation, two identical target stacks are irradiated simultaneously: one stack in the beam at zero degrees and one in the beam at 16 degrees to the incident proton direction. The neutron energy spectrum at 16 degrees simulates that of the low energy tail at zero degrees. Subtracting the normalized yield of the nuclide under study produced at 16 degrees from the yield produced at zero degrees allows the cross section to be calculated at an almost unique neutron energy.

The second technique uses a 'white' neutron beam with an energy range of ~0.1 – 750 MeV generated at the Los Alamos Neutron Science Center (LANSCE), Los Alamos. Neutrons with energies <~0.1 MeV are removed from the beam by 2 inches of polyethylene placed well upstream of the target stack. From these irradiations, 'average' cross sections over this energy range are measured.

The 'average' cross section is good information in itself, but its real value may be to help define the behavior of the cross section as a function of energy for a particular reaction. A calibrated uranium fission chamber is used to measure the neutron fluence through the target stack so that neutron fluences for discrete energy ranges, e.g. from 2.0 – 2.5 MeV, 2.5 – 3.0 MeV etc, can be calculated. These incremental neutron fluences and the cross sections measured at iThemba LABS at unique neutron energies, plus any other reported cross section measurements, are then used to calculate a theoretical 'average' cross section. If this theoretical 'average' cross section agrees with the value measured at LANSCE, then the cross sections used as input to the calculation are probably correct.

The status of the cross section measurements using both experimental techniques is summarized in Table 1, where details of all completed irradiations to produce the nuclides indicated are given. Magnesium targets will be irradiated at iThemba LABS in 2003. After irradiation, the short-lived radionuclides produced in the targets are measured using non-destructive gamma-ray spectroscopy. The cross sections for these reactions have been calculated. The yields of ^{10}Be, ^{14}C, ^{20,21,22}Ne, ^{26}Al, ^{36}Cl, Ar, ^{41}Ca and ^{53}Mn will be measured in these targets using AMS, Mass Spectrometry or other technique as appropriate.

Results and Discussion: Our new cross section measurements for the reactions Al(n,x)^{22}Na and Si(n,x)^{22}Na [7], which are produced by high-energy neutrons only (the thresholds for these reactions are ~30 MeV), and the production of Co isotopes from Ni [5], which are produced by both high- and low-energy neutrons, were used to calculate production rates (PR) in lunar rocks and meteorites. Essential to these PR calculations were the measured 'average' cross sections, which constrained the values of the individual cross sections as a function of energy.

The measured cross sections for Al(n,x)^{22}Na and Si(n,x)^{22}Na at 78 and 114 MeV and the measured 'average' cross sections were used as input to calculate the PR for ^{22}Na in lunar rock 12002 [7], resulting in a calculated PR lower than that calculated earlier when only proton-induced reactions were considered [8] and closer in value to the measured PR. Clearly, for these reactions, the cross sections for neutron-induced reactions differ significantly from those for the corresponding proton-induced reactions.

For reactions with low-energy reaction thresholds, such as those for the production of Co isotopes from Ni, new cross section measurements at high neutron energies appear to have little affect on PR calculations made previously [5]. In part, this is because for these reactions cross sections for neutron-induced reactions have been measured at low neutron energies. However, our new cross sections measurements at high neutron energies were required to reach the above conclusion.

Measurement quality: There are few published cross section measurements for neutron-induced reactions at neutron energies >20 MeV with which to compare our measurements. This makes it difficult to determine whether our measurements are correct.

The cross sections for the reactions C(n,x)^{7}Be and Al(n,x)^{22}Na have been measured at some higher quasi-monoenergetic neutron energies [9]. The cross sections measured in our experiments at iThemba LABS for these reactions are consistent with these historical measurements. This is encouraging and indicates that our measurements are likely to be correct.

The two experimental methods described in this paper can also be used to assess the quality of the cross sections measured at a quasi-monoenergetic neutron energy. The calculated 'average' cross section derived from the cross sections measured at unique neutron energies (plus any additional reported measurements) must be consistent with the 'average' cross section measured at LANSCE. If there is a discrepancy, then the reason for this has to be explored and so the quality of the measurements should be improved. Systematic errors common to both experiments, however, cannot be determined by this method.

Conclusions: The status of the cross section measurements using quasi-monoenergetic high neutron energies and 'white neutron beams is summarized. The 'average' cross section measurements are not only valuable in themselves but also constrain the variation of the cross sections at unique neutron energies as a function of energy. In general, there is reasonable agreement between the cross sections reported here for selected reactions measured using quasi-monoenergetic neutron energies with the few reported historical measurements. This agreement indicates that it is likely that our cross section measurements are correct.

Table 1: targets irradiated/scheduled

	Neutron energy (MeV)				
Product	71	78	114	154	average
^{7}Be	Mg*		C, Si Mg*		C, SiO_2 Al, Mg
^{10}Be	SiO_2 Mg*		SiO_2 Si, Al Fe, Ni Mg*	Fe, Ni	SiO_2 Mg K, Ca Fe, Ni
^{14}C	Mg*	SiO_2	SiO_2 Mg*		SiO_2 Mg
Ne	Mg*		Mg*		Mg
^{22}Na	SiO_2 Mg*	SiO_2 Al	SiO_2 Si, Al Mg*		SiO_2 Si, Al Mg
^{26}Al	SiO_2 Mg*		SiO_2 Si, Al Fe, Ni Mg*	Fe Ni	SiO_2 Mg K, Ca Fe, Ni
^{36}Cl	Ca		Ca Fe, Ni	Fe, Ni	K, Ca Fe, Ni
Ar					Ca
^{41}Ca			Fe, Ni	Fe, Ni	Fe, Ni
^{53}Mn			Fe, Ni	Fe, Ni	Fe, Ni
^{46}Sc			Fe		Fe, Ni
^{48}V			Fe, Ni	Fe, Ni	Fe, Ni
^{51}Cr			Fe, Ni	Fe, Ni	Fe, Ni
^{52,54}Mn		Ni	Fe, Ni	Fe, Ni	Fe, Ni
^{56,58}Co	Ni	Ni	Ni	Ni	Ni
^{57,60}Co	Ni		Ni	Ni	Ni
^{56,57}Ni		Ni	Ni		Ni

*irradiation scheduled for mid 2003

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